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HYSTERETIC LOSS REDUCTION IN STRIATED YBCO

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Hysteretic loss reduction in striated YBCO

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Abstract

Magnetization vs. applied field measurements (M–H loops) were taken on short samples of $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films which were divided into narrow filaments. The YBCO was deposited using pulsed laser deposition onto single-crystal $LaAlO_3$ substrates, with a range of film thicknesses from 0.25 to 0.33 μm. Using a YAG laser, the thin films were patterned into linear striations by removing strips of the superconductor by laser ablation. The resulting striated filamentary structure serves to reduce the effective width of the YBCO films and hence the hysteresis loss in the superconducting samples. The magnetization measurements were taken over the temperature range of 4.2–77 K in applied fields of 0–17 kOe using a vibrating sample magnetometer. The measured hysteresis losses show a highly linear relationship between superconductor filament width and hysteresis loss as anticipated. However, the laser ablation process did result in the redeposition of YBCO along the edges of individual filaments. Degradation of T_c and J_c due to the ablation process is discussed.

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1. Introduction

Current densities greater than 10^6 A/cm^2 at 77 K, self-field, as well as the ability to maintain high current densities in applied magnetic fields, indicate the potential of YBCO thin films in ac applications [1–3]. However, the architecture presently being developed for high temperature superconducting (HTS) coated conductors is primarily for dc environments [3–6]. The YBCO films used in coated conductors are characterized by high aspect ratios, with widths up to a centimeter compared to thicknesses in the range of 0.3 to several μm. With applied magnetic fields normal to the c-axis, these high aspect ratios can lead to unacceptable hysteretic losses in ac applications of the HTS coated conductors such as motors, generators, transformers, etc. [1,2,7].

To minimize these losses, Carr and Oberly suggested a design for a low ac loss coated conductor [4]. This design calls for the coated conductor to be subdivided into thin linear filaments, or striations, and then for the tape as a whole to be twisted. This protocol, paralleling the configuration of more traditional "wire" conductors tends to decouple

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the filaments and lower the hysteretic ac losses, while avoiding problems associated with more convoluted current paths. In the design of Ref. [4], it is suggested that the superconducting filaments be separated by highly resistive barriers. This is compatible with the use of Ni-alloys substrates, which have a moderately high resistance [8,9].

There are many possible approaches to producing the desired linear striations in the structure of YBCO coated conductors, and they will not be enumerated here. Laser ablation is used for the present work since it is fast, repeatable, and readily available. The precision and width of the cuts is limited only by the choice of laser and offers a ready demonstration of the striated conductor. This work focuses on the potential of this low ac loss design with respect to the use of a striated superconducting film and the subsequent reduction of the hysteretic loss term.

2. Experimental

2.1. Sample preparation

YBCO was deposited onto single-crystal $LaAlO_3$ (LAO) substrates by pulsed laser deposition as described elsewhere [10,11]. The LAO substrates measured 3.2 mm × 12 mm and the deposited YBCO films varied in thickness from 0.25 to 0.33 μm. A YAG laser was used to ablate the film at room temperature at atmospheric pressure to create the striations in the YBCO films as shown in Fig. 1. The actual ablations were performed by Mound Laser & Photonics Center, Inc. [1] The beam energy was reduced to mitigate the thermal effects on the YBCO film, and a steady flow of argon gas aided in the removal of the ablated film. Samples were created with average filament widths of 82, 254, and 492 μm. The cuts between filaments, where the YBCO was ablated, ranged in width from 49 to 82 μm on each of the samples. The striated samples, as well as a control (non-striated) sample, were taken from a single batch of processed samples. Magnetization measurements were performed using a vibrating sample magnetometer (VSM) in conjunction with a 17 kOe electromagnet. M–H loops were measured for temperatures ranging from 4.2 to 77 K; all magnetization measurements were taken with the applied field parallel to the c-axis (perpendicular to the sample face).

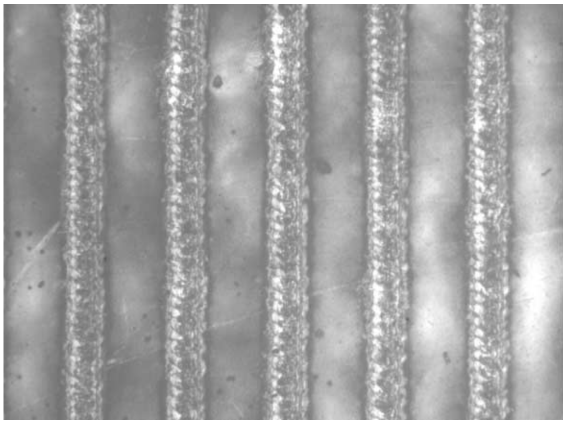

Fig. 1. Striated filament structure of YBCO created by laser ablation (superconducting filament width average of 254 μm and cut width average of 66 μm).

2.2. Hysteresis loss

From Carr and coworkers [1], the loss per unit volume per cycle of a superconducting strip with no transport current is given by

$$\frac{Q}{V} \approx \frac{1}{10} d J_c H_0 \tag{1}$$

where $d = 2a$ is the width of the superconducting strip, J_c is the current density, and H_0 is the field amplitude which is large in comparison with H_p, the field required for full penetration. The units used here are cgs-practical (A, cm, Oe). To convert the losses to SI, insert μ_0 and multiply by 10. For large aspect ratios a/b, where a is the half-width and b is the thickness of the YBCO,

$$H_p \approx J_c \frac{2b}{10\pi} \left(\ln \frac{a}{b} + 1 \right). \tag{2}$$

The field profile for the magnetization measurements in this work was triangular with a maximum field amplitude of 17 kOe.

[1] Mound Laser & Photonics Center, Inc., 7220 Mound Avenue, Miamisburg, OH 454342-6714, USA.

3. Results and discussion

3.1. Effective superconducting filament width

Profilometry measurements were used to determine the nominal filament thickness, d_{nom}, for our striated samples. Fig. 2 shows an example of a profilometry result for one particular sample. These detailed measurements revealed an adverse effect of the laser ablation procedure: the build-up of re-deposited YBCO along the edges of each cut. Although not observable using conventional microscopy techniques, the boundary region of the re-deposited YBCO is clearly seen in Fig. 2.

It is not immediately clear if d_{nom}, which is defined to include the re-deposited regions of the filaments, will represent the true filament width or not, since we do not know how much, if at all, the re-deposited YBCO affects the current-carrying capability of the film. Additionally, it should be noted here that d_{nom} is an average parameter, which for each striated sample is an average of the profilometry results. However, the control sample of YBCO thin film was not patterned using the laser and thus the physical measurement of the width of this sample is indeed the true filament width. We can attempt to determine the true filament width (i.e., how much of the filament is superconducting) by measuring its superconducting properties magnetically, and we will denote this the effective filament width, or d_{eff}. From Eq. (1), the hysteretic loss should be proportional to the filament width d. We can then define a d_{eff} value (in μm) for each striated sample from

$$d_{eff} = 3220\left(\frac{Q_{striated}}{Q_{non\text{-}striated}}\right) \tag{3}$$

since the width of the non-striated filament measures 3220 μm. If the re-deposited conductor does not degrade (or enhance) the current-carrying capability of the filament, d_{nom} should equal d_{eff}.

3.2. Loss reduction

From magnetization measurements, the hysteretic loss is determined by

$$Q_h = \int M\,dH \tag{4}$$

which is the area of the M–H loop. Fig. 3 displays the M–H loops for all samples at 4.2 K. The general agreement of these results with Eq. (1) is clear—a significant decrease in loss for striated samples. Notably, the loss from the non-striated sample is almost two orders of magnitude greater than the loss for the sample $d_{nom} = 82$ μm. In order to compare these results in more detail, we can calculate the largest penetration field according to Eq. (2). For the un-striated film that was measured, using a ΔM of about 4×10^5 emu/cm^3 at field penetration, we get a critical current density of about 2.5×10^7 A/cm^2 (at 4.2 K). Using this

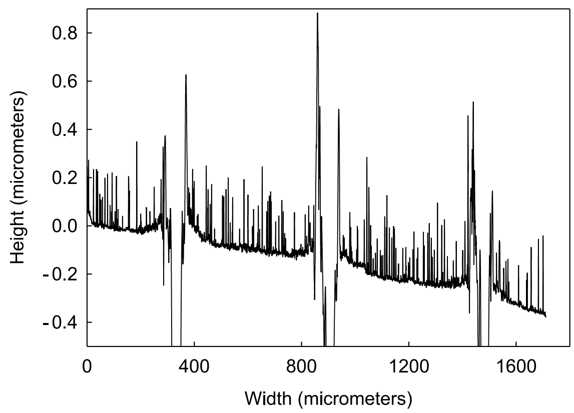

Fig. 2. Profilometry results of the 254 μm-filamented sample. The sharp valleys represent the ablated area. The build up of re-deposited YBCO is visible on the edge of the cuts.

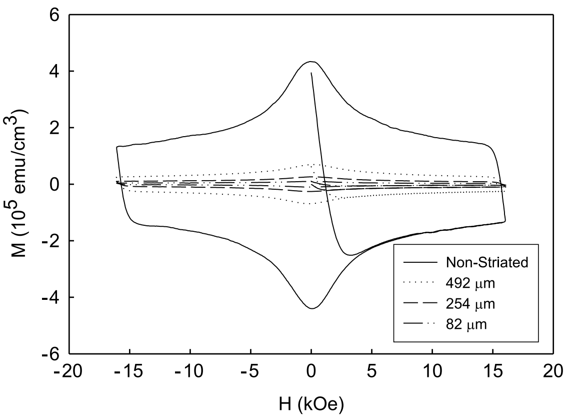

Fig. 3. M–H loops for all samples of 4.2 K.

number, in conjunction with $a = 0.16$ cm and $b = 0.25$ μm, we find that $H_p = 3.89$ kOe, which is near the experimental result. However, it is clear that the condition $H_0 \gg H_p$ is not fulfilled. Nevertheless, by comparing Eqs. (19) and (21) from [12], we can see that even as low as $H_0 \approx 2.7H_p$, Eq. (1) is roughly applicable, with a prefactor (for $H_0 \approx 2.7H_p$ it is 2 but it is varying strongly in this region). The question then becomes how linear with width this expression remains. We have answered this question experimentally by plotting the volumetric hysteretic losses as a function of filament width d_{nom} in Fig. 4a. Fig. 4b is the same plot scaled to show the effectiveness of the striations. As we would have expected from a straightforward application of Eq. (1), the loss is directly proportional to the filament width. The data are highly linear over the entire range of temperatures. It is expected that the prefactor for Eq. (1) is changing, based on the results of [12]. However, the losses are seen experimentally to at least be proportional to d_{nom} to a high degree, as indicated by Eq. (1).

The data shown in Fig. 4 provides clear evidence that striation of YBCO coated conductor is indeed beneficial for the reduction of hysteretic losses. It also shows that laser patterning is an effective method for creating the striations. As indicated above, they follow Eq. (1) in that Q is linear in d_{nom}. To this extent, they also fail to show any deviation from non-linearity that might arise from degradation of superconducting properties in the redeposition zones. If present, these effects

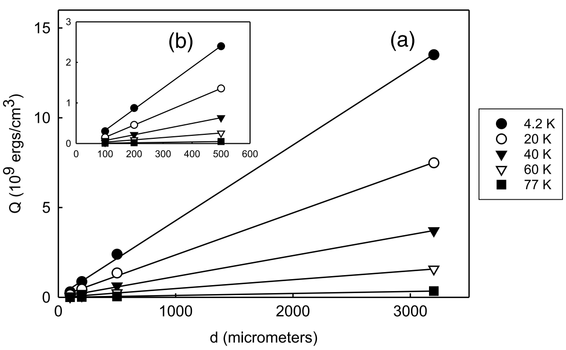

Fig. 4. Hysteretic loss for four different samples measured at various temperatures: (a) three different striation widths and control sample, (b) blow-up of (a) for the three striation widths.

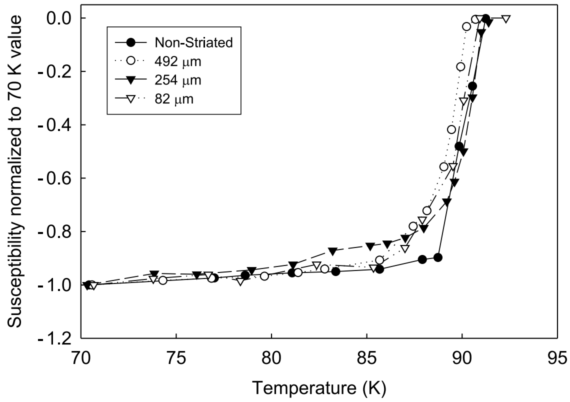

Fig. 5. dc Susceptibility curves for all samples.

must be small. In order to further investigate this, we used the VSM to measure dc susceptibility curves using a field of 2 Oe. As shown in Fig. 5 the susceptibility curves for the striated films are slightly more shallow as compared to the sharp transition of the non-striated films, possibly pointing to some small level of degradation in the YBCO. This may be a result of the small amounts of re-deposited YBCO during the striation ablation process. Even so, the change in the susceptibility curves is minor, and the influence on magnetization, and thus presumably J_c, null.

Normalizing the loss, Q_h, of each sample to the filament width provides a means of detecting even a small variation of loss with filament width. The non-striated sample can serve as a basis for comparison since d_{nom} is exactly d_{eff}. The hysteretic loss of the samples normalized to their respective filament widths was plotted at various temperatures in Fig. 6. There is no clear evidence from these curves of deviation from Eq. (1) among the striated samples; while d_{nom} is less than d_{eff} for the two smallest filaments, the opposite is true for the 492 μm filament sample. The variation in d_{nom} from the profilometry results introduces sufficient noise into the data that the differences seen are probably not meaningful. This would seem to suggest both that the linearity with d_{nom} described by Eq. (1) is followed for these samples, and that J_c is not noticeably degraded by the patterning. Notably, the variations in the measured filament widths were

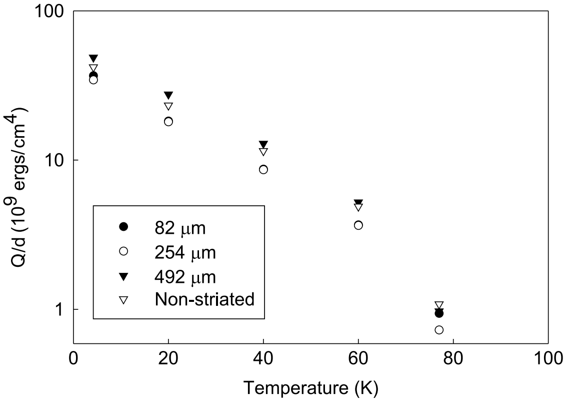

Fig. 6. Volumetric Q_h normalized to d_{nom}.

approximately 20%, which is on the same order as the variations in the normalized Q_h/d_{nom} data.

4. Conclusions

A striated, multifilamentary structure of quality YBCO on LAO was successfully created for reducing the hysteretic loss of HTS coated conductors. A laser ablation technique was used as an effective means of subdividing the filaments to reduce the high aspect ratio of the coated conductor—although many other methods are possible. We found that hysteretic losses decreased linearly with YBCO filament width. Even though susceptibility curves show a slightly sharper transition for non-striated films, there is no evidence from the Q_h results that J_c is affected by the striations in any significant way.

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